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OXYGENATION OF AQUEOUS BODIES USING LIQUID OXYGEN-LOXINATION

T. D. Bath, et al

Midwest Research Institute

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16. Abstract

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INTRODUCTION

Rationale

One of the basic problems in water pollution control is that of supplying dissolved oxygen (DO) to a body of water at sufficient rates and in sufficient quantities to prevent septicity due to bacterial metabolism of organic impurities. This problem can occur either in a sewage treatment plant, or in a stream or river, when the organic load becomes so great that the natural diffusion process cannot supply the amount of oxygen required. In such cases, artificial processes for increasing the DO concentration can be used, including mechanical aeration methods. The present program was initiated to investigate the possibility of using liquid oxygen (LOX) to replace these aeration processes; i.e., using liquid oxygen as a source of dissolved oxygen for aqueous bodies. We have designated this process as "LOXination."

The rationale for considering LOXination in wastewater treatment and for stream or impoundment aeration is as follows:

1. Usually the most economical form for transportation of oxygen is the liquid state, LOX.

2. LOX is more dense than water. If slugs of adequate size are injected into an aqueous body, they should sink to the bottom and thus limit direct losses to the atmosphere.

3. LOX, when injected into water, could evaporate at rates that would produce a higher pressure bubble than can be obtained by sparging of gaseous oxygen; therefore, use of LOX could yield improved mass-transfer rates.

4. Evaporation of LOX in an aqueous matrix should lead to localized cooling which would increase the driving force for mass transfer.

5. LOX, when injected into water, could impart increased turbulence to the system, thus increasing the rate of solution.

6. If moderate sorption efficiencies (on the order of 50%) could be achieved in field application, use of LOX for large aqueous bodies would be cheaper than mechanical aeration.

The Phenomenon

Liquid oxygen and liquid water cannot coexist except under very artificial and extreme laboratory conditions. Any study of the transport of LOX into water must of necessity concern itself with transient situations where it is questionable whether the LOX itself ever comes into direct contact with liquid water.

Liquid oxygen has a density at -183°C of 1.142 g/ml. It would be expected that LOX would sink in a body of water and form a pool at the bottom from which it would evaporate and then dissolve. A report[1/] of a large dump of surplus LOX in the Houston ship canal advised that the LOX sank to the bottom and dissolved without producing any surface ebullition. Preliminary tests at MRI seemed to corroborate this report.

Once in contact with liquid water, LOX should rapidly evaporate. The heat content of 0.31 ml of water at 20°C is sufficient to vaporize 1 g of the LOX. The gas that would be produced by 1 g would occupy 230 ml at -183°C and at 1 atm. Conversely, if the gas produced were confined to the space occupied by the liquid, a pressure of 263 atm would be needed. The actual system of vaporizing LOX in water surely involves a bubble of pressure intermediate between 263 atm and the hydraulic head of the water body. As the bubble expands, it must overcome the inertia of the surrounding water. The exact formulation and solution of the kinetic equations that analyze the system shown in Figure 1 are beyond the scope of this program. Heat flows into the LOX according to the equation

$$\frac{dQ}{dt} = K_H A_1 \frac{dT}{dx}$$

where Q is the heat transferred in time "t", K_H is the heat-transfer coefficient, A_1 is the effective transfer area, and T is the temperature difference across the distance "x". The amount of LOX evaporated is the heat transferred divided by the latent heat, λ .

Oxygen transfers into the water according to the relation

$$\frac{dOx}{dt} = K_G A_2 (P_t - P_s)$$

where Ox is the amount of oxygen transferred into the water phase, K_G is a mass-transfer coefficient, A_2 is the effective area through which the oxygen is transferred, P_t is the pressure in the gas envelope at time t, and P_s is the vapor pressure of O_2 at saturation.

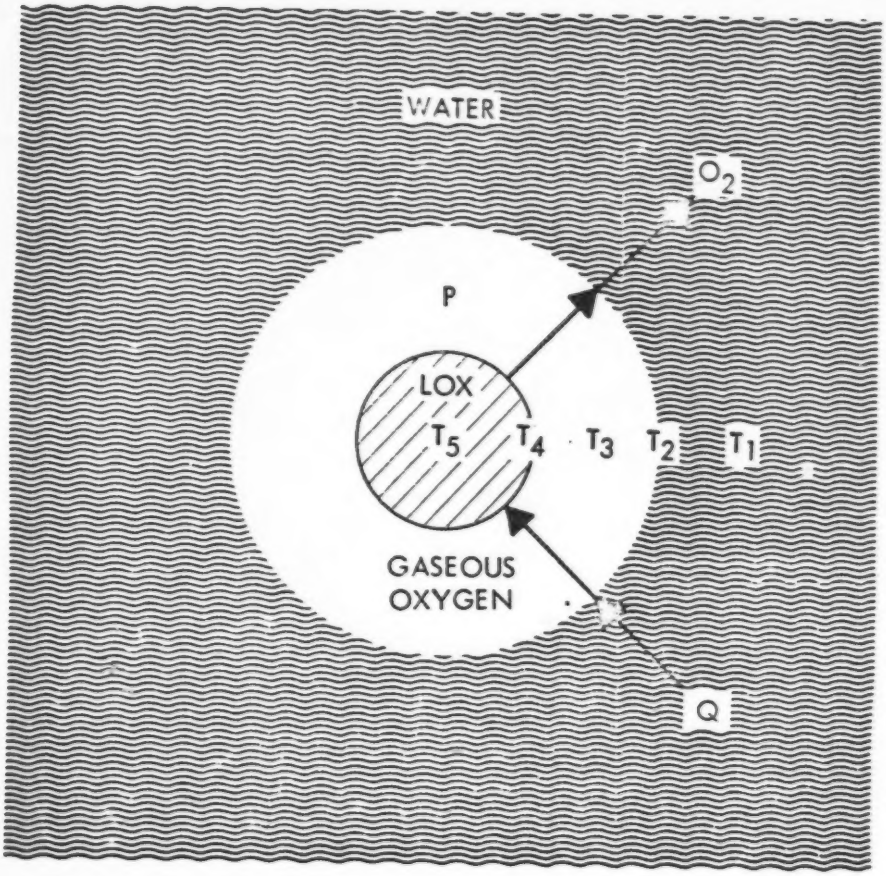

Figure 1 - Simplified Schematic of LOX Dissolving in Liquid Water

The accumulation of oxygen in the gas envelope is "n" of the general gas equation, PV = nRT. Thus

$$\frac{P_t V}{RT} = \frac{1}{\lambda} K_H A_1 \frac{dT}{dx} - K_G A_2 (P_t - P_s)$$

where V is the volume of the gas envelope and, therefore, a function of the radii of the LOX sphere and the gas sphere. Likewise, A_1 and A_2 are different effective areas, but both are dependent on the radius of the gas sphere. The distance of the heat transfer, "x", is also a linear dimension. With further examination, it is recognized that P and T, being related to V, are also related to the radius, as are the constants λ, K_H and K_G since they are functions of T . The result is a transcendental equation with no closed-form solution.

Nonetheless, if (1) heat transfer, (2) LOX boil-off, and (3) transfer of oxygen from the gas envelope occur under high pressure, nonequilibrium conditions (to be expected due to the inertia of the water), there should be a more rapid solution of injected LOX than injected gaseous oxygen.

A similar argument can be made that the turbulence due to high thermal gradients in the water surrounding a sphere of LOX in a gas envelope would be greater than around a simple gas bubble.

Scope and Objectives of the Program

The program tasks can be separated into two broad areas: (1) information retrieval and generation, and (2) evaluation. The objective of the first task area was to develop enough information, both through literature review and experimentation, to permit us to perform the second task area adequately: assessment of the appropriateness of LOX as an oxygen source in oxygen-poor waters. The "Scope of Work" agreed upon by Midwest Research Institute and the FWQA is attached as Appendix A which details the experimental and evaluative objectives of the program more fully. This report documents our efforts to fulfill the letter and the intent of the "Scope of Work," and delineates the difficulties and extenuating circumstances which we encountered in these efforts and which have led to our present inability to perform a really definitive assessment in this report.

PROGRAM REVIEW

State of the Art Review

A literature survey was conducted at the beginning of the program to obtain as much information as possible pertaining to the injection of liquid oxygen into water. This survey was continually updated during the program. The particular key words used in the search include: sewage treatment, aeration, mass transfer, liquid oxygen, and gaseous oxygen. We have found that very few studies have been conducted using pure gaseous oxygen, or air enriched with oxygen, for increasing the DO content of aqueous solutions. No studies were found in which liquid oxygen had been used for this purpose.

The reviewed literature was divided into five groups: (1) pure oxygen or enriched air, (2) mass-transfer coefficients, (3) transfer in activated sludge processes, (4) effects of surface-active agents, and (5) general. During the past decade, Amberg[2] studied reaeration of streams with molecular oxygen, and McKinney[3] studied oxygen-enriched air for biological waste treatment. All other reported work using pure gaseous oxygen was done more than 10 years ago. References that are not cited in the text of the report but that are considered relevant are included in the Bibliography (Appendix B).

Few data were available on the mass-transfer coefficient that might be expected when pure oxygen or enriched air was used, and none were available for liquid oxygen. Several articles were obtained in which mass-transfer coefficients were calculated for the transfer of oxygen from air. Also obtained were several articles on the transfer of oxygen in activated sludge processing, using both mechanical aeration and the diffused air process. The effect of surface-active agents on the transfer of oxygen has received a great deal of study because of the presence of these compounds in most treatment facilities. Mancy and Okun[4] and Eckenfelder[5] have all been very active in this area.

Reprints of the most pertinent pieces of literature were obtained at the beginning of the project. A bibliography of this literature is presented in Appendix B. This bibliography was added to as the program progressed, but in general, little of real pertinence to the program was found.

Concomitant with this program, the FWQA has had work under contract to investigate the potential of pure gaseous oxygen in secondary treatment. This gaseous oxygen program has been conducted at Batavia, New York, by Union Carbide. The results of the Union Carbide program should help evaluate the need for further investigation of LOXination.

Equipment Design and Construction

Design basis. The design of the experimental apparatus used in these studies was tailored so as

1. To provide experimental data over the range of process variables specified in the "Scope of Work,"

2. To be reasonably easy to control and operate, and

3. To restrict costs to the budgeted amount in the contract.

This third item furnished the limiting constraint on the size of the apparatus. This, in turn, specified that extremely low amounts of LOX be injected in order to operate the system at reasonable sorption efficiencies. Although we were unable to obtain information from LOX processors and handlers regarding the design of devices to handle such low flows of LOX, it was our feeling that the problem could be solved by the development of a special LOX injection device. A description of the major components of the apparatus, as well as a schematic flow diagram, an instrument circuit diagram, and photographs of the completed apparatus, are all presented in Figures 2 - 5.

Construction. The fabrication and assembly of all of the major components of the apparatus, except the LOX-injector device, did not present any unusual difficulties. These injectors were used during the course of the project. Schematic designs of the last two are shown in Figures 6 and 7. The initial design used a vacuum jacket to maintain the oxygen in the liquid state. Flowrate was controlled by a needle valve in series with a toggle-type valve which was used to shut off flow (and also to remove ice formed at the end of the injector). Tests with this device showed that the design did not provide adequate insulation to guarantee that the injected LOX would be vapor-free. This injector was then rebuilt so that the valves and tubing that were in direct contact with the LOX were jacketed with a liquid-nitrogen bath. This device would dispense LOX which seemed to be free of vapor, although problems were encountered with the formation of ice on the injector tip. Although some rather unusual procedures had to be used to make this device operate (discussed below under Operating Procedures), it was used during most the experimental runs described below.

Later in the program, there arose the need for a device that would dispense LOX continuously into the water column. Since the injector shown in Figure 6 developed leaks, it was simpler to construct a new device that would incorporate in its design the experience of several months of laboratory study. This third injector design consisted of several concentric tubes. The inner tube carried LOX, the next two carried a continuous stream of liquid nitrogen, and the liquid-nitrogen-containing tubes were surrounded by insulation. Flow was controlled by the tip orifice and the

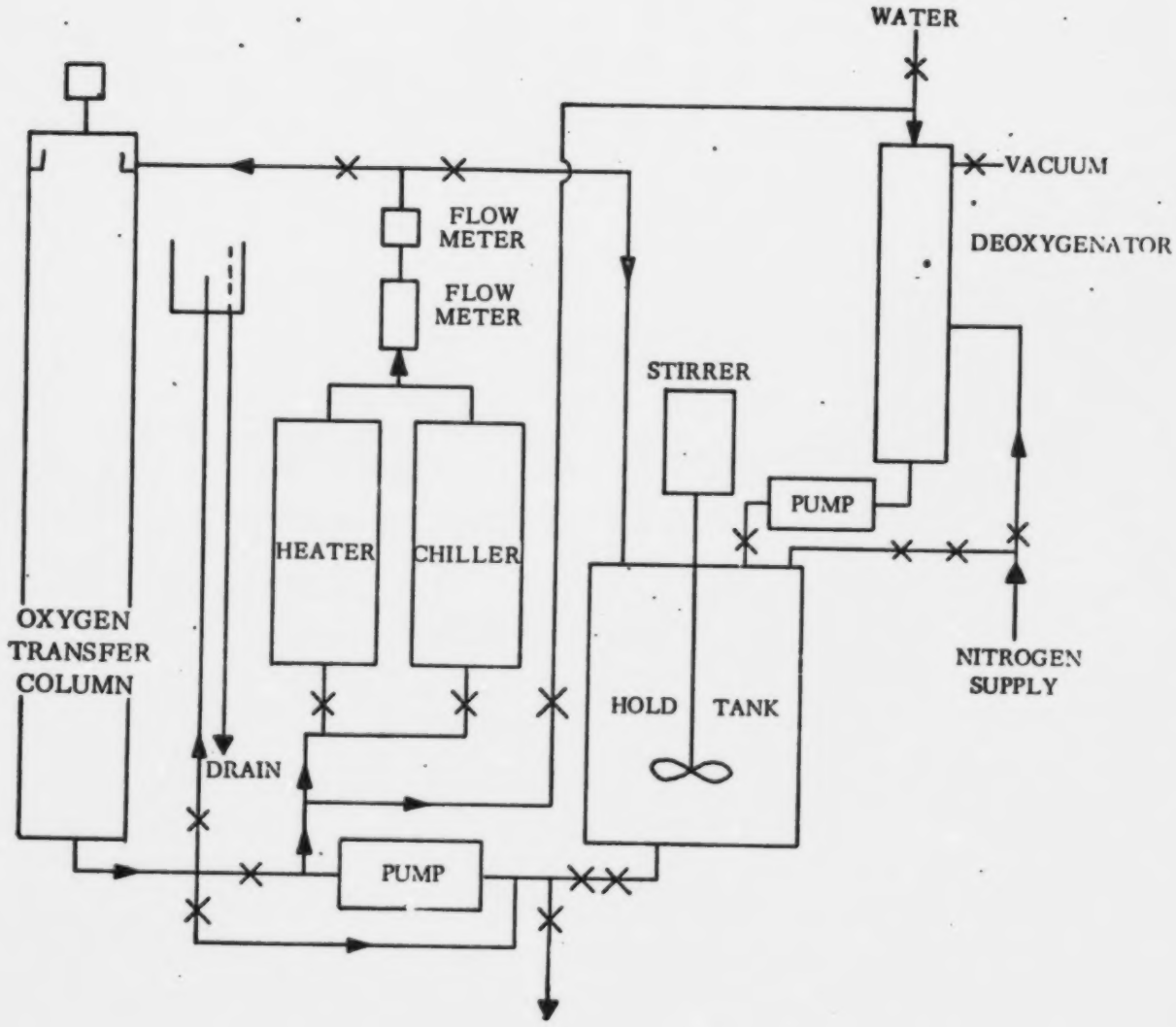

Figure 2 - Water-Flow Diagram for LOXination Equipment

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-Figure 3-

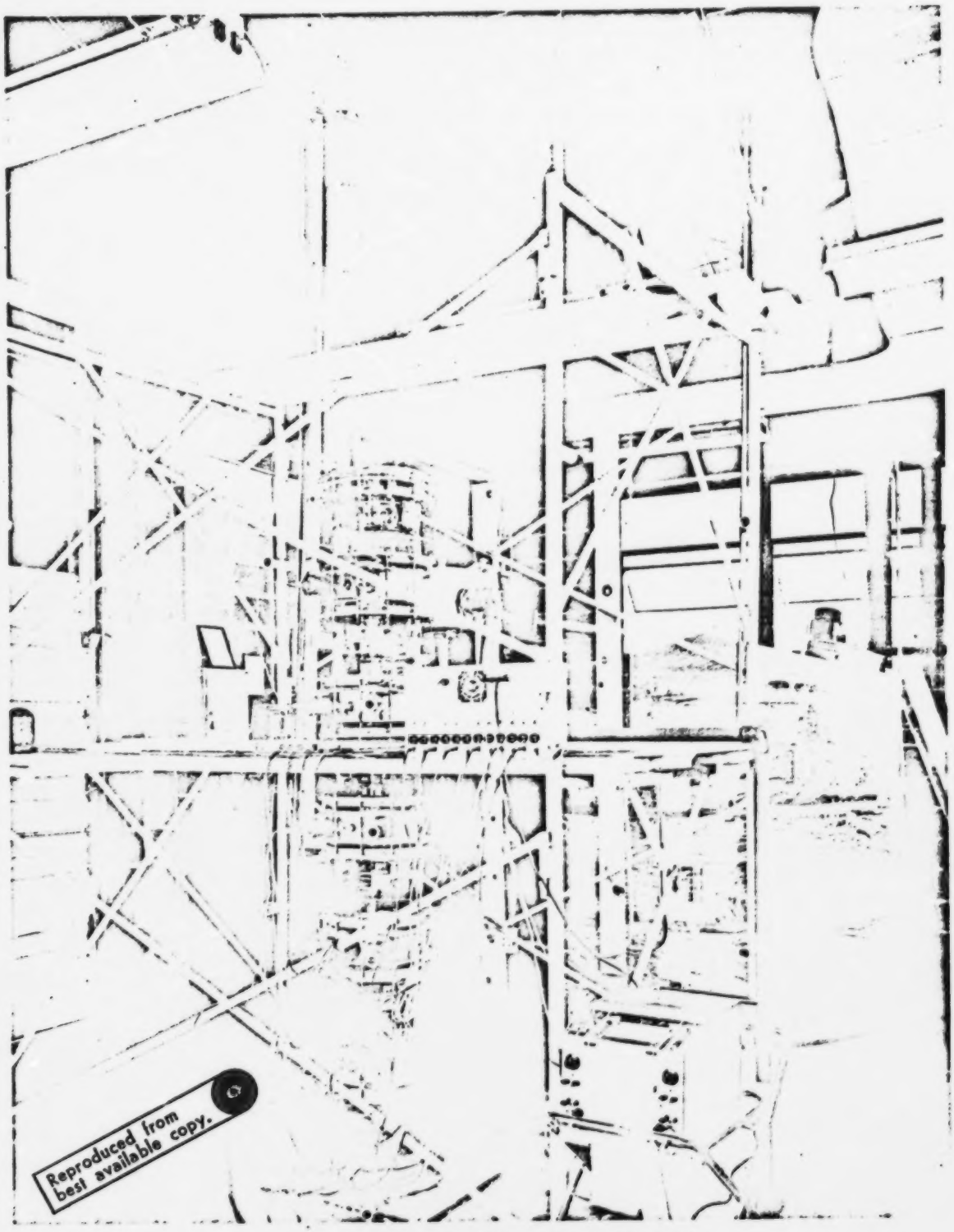

Figure 4 - LOXination Equipment

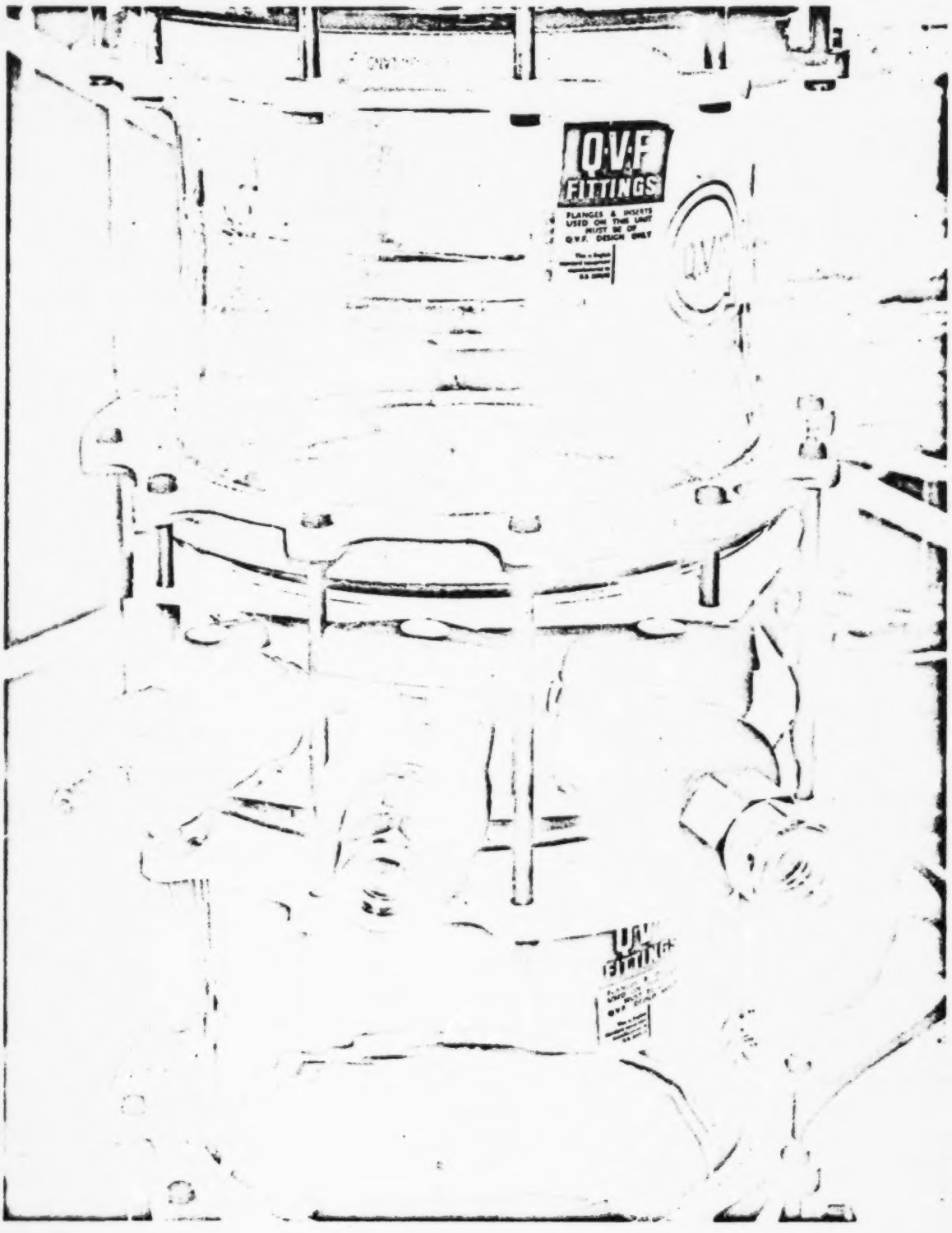

Figure 5 - Close-Up of LOX-Absorption Column

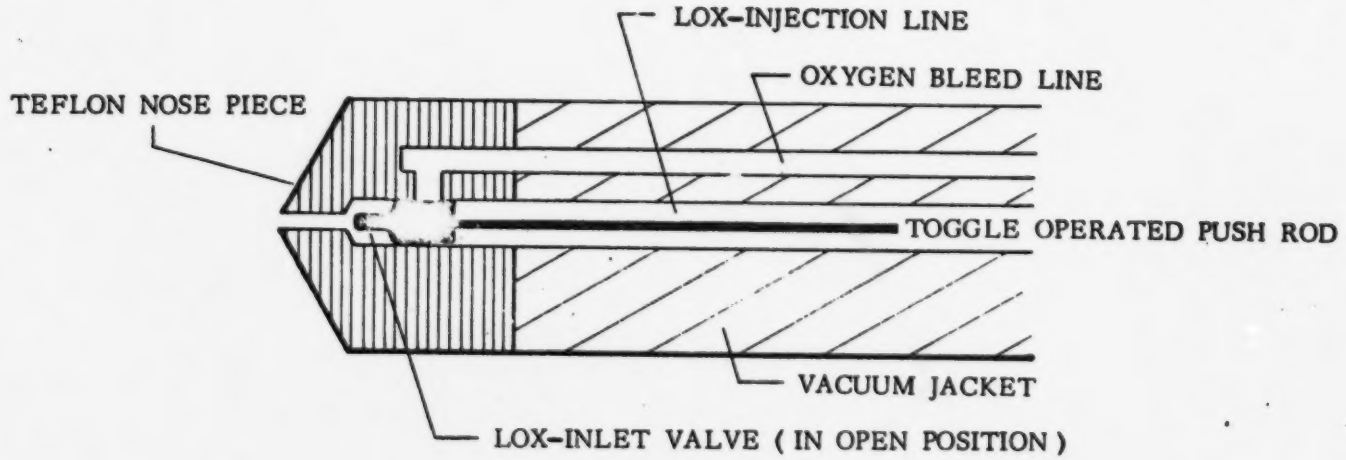

Figure 6 - Nose Piece of First LOX Injector

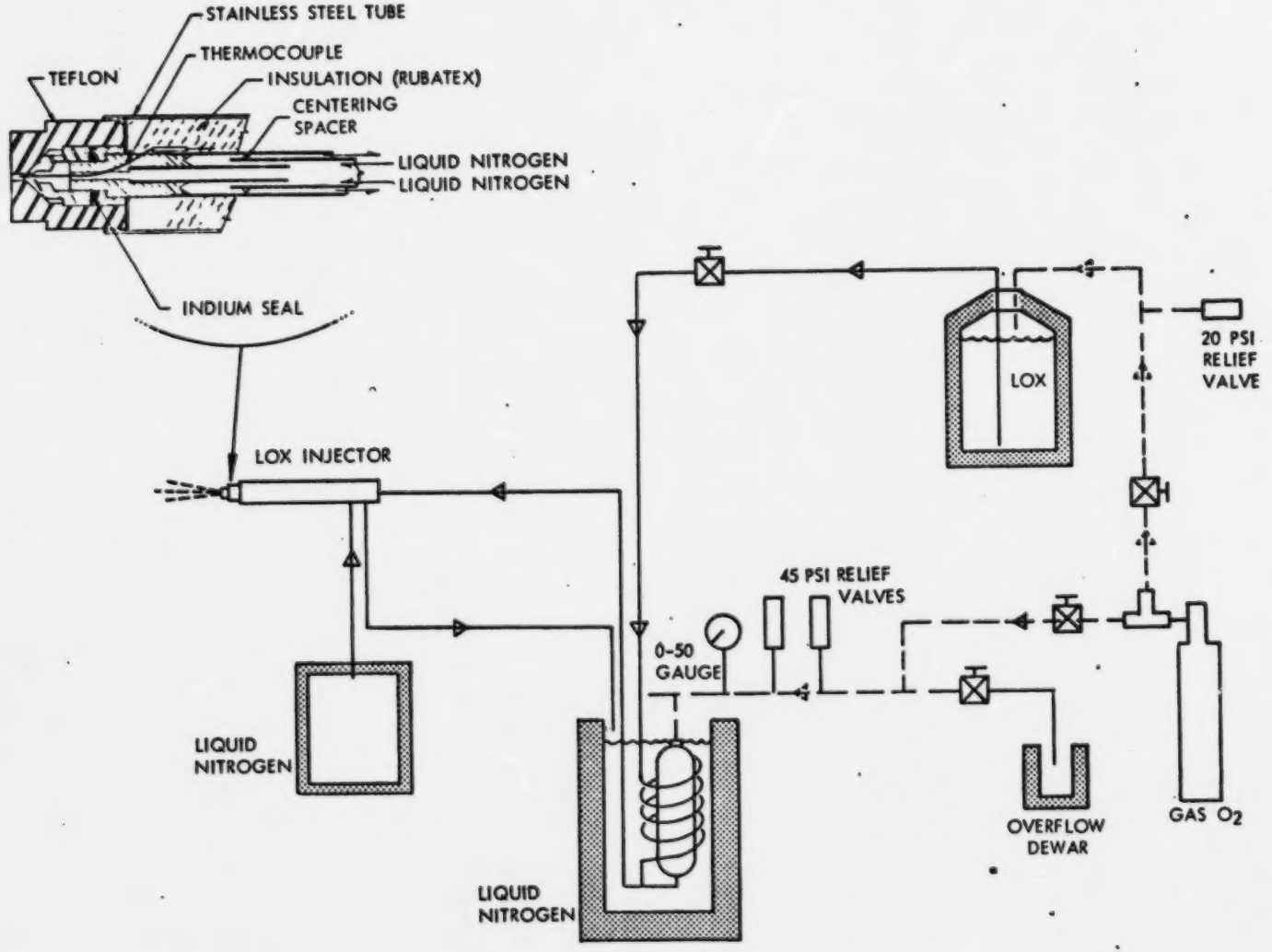

Figure 7 - Schematic of Injector and Associated Apparatus for Continuous LOX-Injection Experiments

back-up pressure. A thermocouple was placed as close as possible to the point where the LOX entered the water. A continuous flow of 25 g/min of LOX into the water column could be maintained without icing until the LOX reservoir was emptied. It is worthy of mention that we were not able to develop a device that would permit the extremely low, LOX flowrates demanded by the dimensions of the rest of the apparatus.

Operating Procedures

The test system had been designed so that experimental runs could be conducted over a wide range of variables; e.g., water flow from 0 to 31 gal/min and temperatures from 4° to 30°C. The second LOX injector had been designed so that LOX injection rates could be varied from about 1 g/min up to 40 g/min with either continuous or intermittent injection.

The DO content and temperature that were attained in the absorption column during an experimental run were monitored with DO and temperature probes which allowed measurement of both longitudinal and radial profiles. These probes were calibrated at the beginning of each day's experimental runs. The automatic switching device (see Figure 3) was set so that temperature and DO measurements were taken continuously at each longitudinal position in the column. In this manner the entire column was scanned every 15 sec, with the measurement at each longitudinal position being of 2-sec duration.

Before experimental runs were conducted, it was necessary to obtain a supply of water with the desired DO content. This was done by deoxygenating tap water in a vacuum-stripping column and storing this water under a nitrogen blanket in a 1,500-gal insulated holding tank. The desired initial temperature was obtained by circulating the water from the holding tank through the heater or chiller.

Experiments were conducted both with the water phase being static and with the water flowing downward past the LOX injector. Static runs began by injecting LOX for a predetermined time interval at a predetermined flow. Temperature and DO levels were monitored from before LOX injection until no changes occurred in the DO profile.

A dynamic run was begun by starting the water flow through the column, adjusting to the desired flowrate, and allowing this flowrate to equilibrate. After the water-flow regime had been equilibrated, LOX injection was begun. The increase in DO content of the water in the column was monitored until it returned to the same level as before LOX injection.

The majority of the experimental runs were made using the injector shown in Figure 6. Due to ice formation on the tip of this device, it was necessary to follow an unusual procedure to initiate flow. The needle valve which was used to control flow was opened wide since flow of LOX would not start otherwise. Once flow was initiated, the valve was throttled back to whatever position was necessary to give the flowrate required for the experiment. Since the valve was out of adjustment for a time interval that was brief in relation to the 30-sec or longer LOX-injection period, it was initially felt that this procedure introduced little experimental error. Closer examination of the data, however, revealed that the initial slug of LOX put in by this procedure could be an important fraction of the total LOX input. This information has caused us to hold suspect a large number of the data taken on the program.

For the continuous runs that were conducted to compare the sorption of gaseous oxygen and LOX, the injector shown in Figure 7 was used. LOX flow was started with the water surface below the tip of the injector. Once steady LOX flow had been established, as indicated by the flow of exhaust gas (measured by a wet-test meter), the water column was raised to the top of the apparatus; while LOX injection continued and the desired water flow through the apparatus was set. Only with this procedure could we prevent plugging of the LOX injector with ice. A thermocouple at the injector tip demonstrated that LOX at -183°C was being ejected. Further evidence for the injection of oxygen largely in the liquid state was the magnitude of oxygen flow through the system. The tip orifice would not have permitted this amount of gas flow with the pressure employed.

The LOX and water streams were maintained constant until the DO in the exit flow showed a constant level. The exhaust flow of oxygen that was indicated by a wet-test meter also indicated steady sorption conditions.

Experimental Program

Rationale. The purpose of the experimental program was to determine the influence of several operating and system parameters on the rate and efficiency of transfer of LOX into the aqueous phase. The influences of these system parameters were to be determined experimentally by varying one system parameter while holding the others constant. Factorial experimental design was employed because a thorough study of the total number of experimental conditions would have been prohibitively expensive.

Chronology of Experiments. As noted above, the construction of the experimental system was accomplished with little difficulty with the exception of the LOX-injector device. A modification of the original design

produced what we felt was a satisfactorily operating device. After "checking out" the system, we proceeded to obtain a large quantity of experimental data according to the statistical experiment plan. More than 300 experiments were conducted to study the effect of LOX flowrate, water flowrate and LOX-injection time on oxygen sorption and transfer rate in:

1. The cylindrical column,

2. The column with cross-flow baffles installed throughout its length,

3. The baffled column with an additional, small-diameter extension on top,

4. System (3) at variable-inlet water temperatures,

5. System (3) with variable-inlet water DO,

6. The cylindrical column (with and without the extension) having an impeller mounted just superior to the LOX-injection point (a 4-in. impeller rotated at 680 rpm by a 1/10 h.p. motor, and a 6-in. impeller rotated by 1/3 h.p. motor at 1,720 rpm, were used at different times).

7. System (6) used to compare the sorption of LOX in relation to gaseous oxygen.

As pointed out earlier (under Operating Procedures), suspicion as to the reliability of the amount of injected LOX led us to conduct continuous runs. A few runs were made with this system in an attempt to compare sorption efficiencies for LOX with those for gaseous oxygen. This was the last set of experimental measurements performed on the program. Attention was then turned to an attempt to draw useful conclusions from analysis of the data at hand.

THE EXPERIMENTS

In this section of the report, we will deal with the experimental measurements themselves, their analysis and their validity. The data are presented in tables that include all those experiments with a particular, experimental apparatus arrangement or process variable.

Experimental Analysis

Material Balances. The LOX injector, in all runs involving the injection of slugs of oxygen, was situated 14 in. from the bottom of the column with the tip in the center of the cross section. The DO content was measured at six height positions in the column. The lowest measurement point is of greatest importance to the dynamic runs because it indicates the outlet DO content. Figure 8 shows a typical curve of time versus DO content where the time is measured from the start of LOX injection. This particular curve is for Run No. 22. To calculate the efficiency of absorption, the area under the curve was determined, multiplied by the mass flow of water and divided by the amount of LOX injected. The LOX-injection system was calibrated by continuous flow. The DO probes were calibrated against air-equilibrated water. The overall, oxygen material balance was generally not checked by measuring the quantity of gaseous oxygen evolving from the top of the sorption column until very late in the program when it became apparent that the oxygen material balance was in question. The gaseous oxygen flow was calibrated by weight-difference measurements and checked with a wet-test meter.

Reproducibility. During all but the final phases of the experimental program, replicate runs showed good precision. The results obtained in three dynamic experiments, during which identical experimental conditions were maintained, are shown in Figure 9. The plotted data are the DO level as measured by the Clark oxygen electrode at the bottom station of the absorption tower.

Near the end of the experimental period, it was discovered that the techniques for injection were not those for which the calibration was made. The LOX-flow calibration in use was not valid. For this reason, the columns of data on efficiency of oxygen absorption in the tables of results are labelled as "relative efficiency."

A graphical technique was used to calculate the absorption efficiency. This technique involved determining the area under the curve of dissolved oxygen versus time for a given run (see Figure 8). The units of the area calculated in this manner are (ppm) x (sec). This area was multiplied by the mass flowrate of water through the column to obtain the total amount of oxygen absorbed during the experimental run. The oxygen injected during the experiment was obtained by multiplying the LOX flowrate by the time of LOX injection. Thus, efficiency was calculated by dividing the LOX injected into the amount of LOX absorbed.

Mass-Transfer Coefficient. These were calculated two different ways. The first method used involves the rate of transfer from the oxygen globule into the water, and the second involves a mass balance and a rate

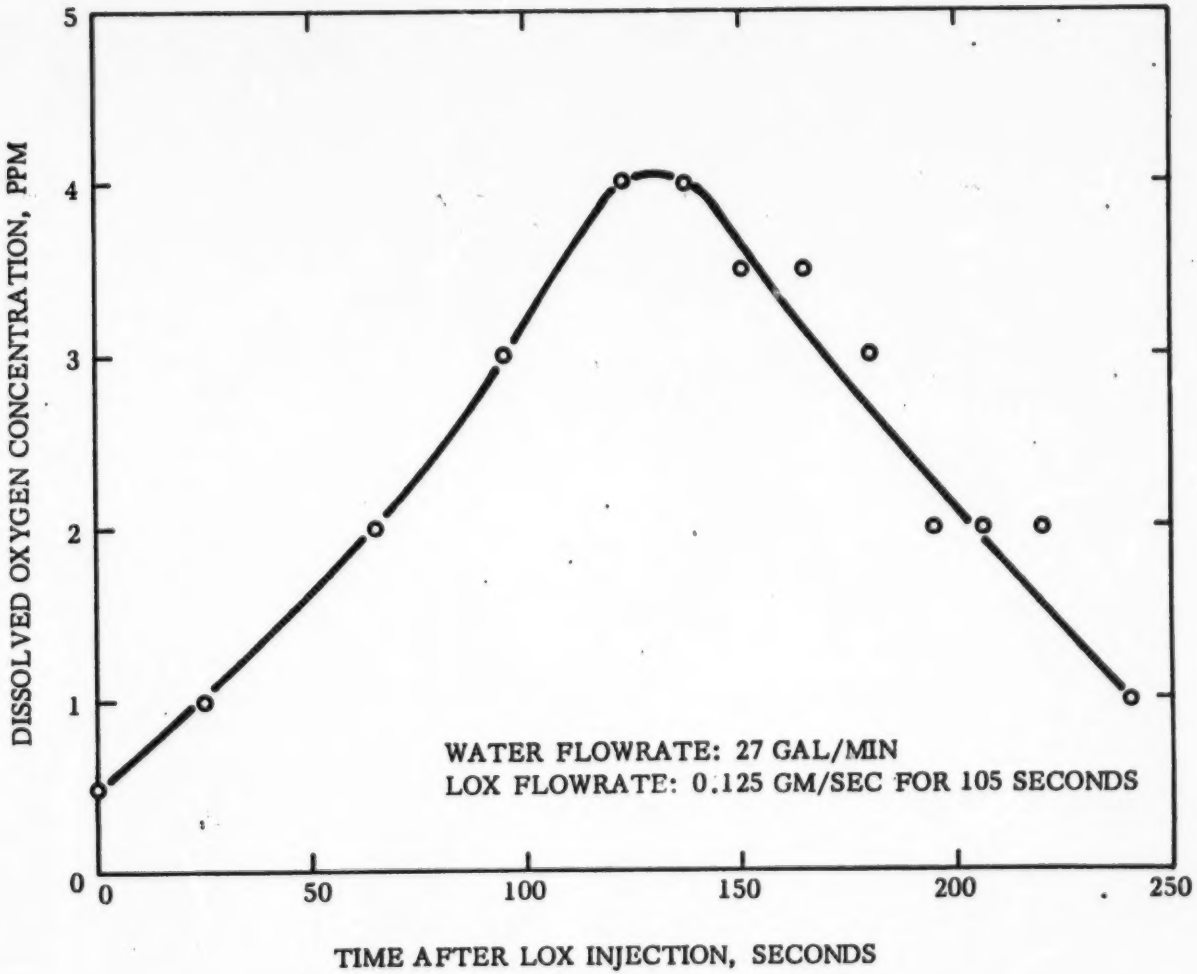

Figure 8 - Typical Curve of DO Versus Time for a Dynamic LOXination Run

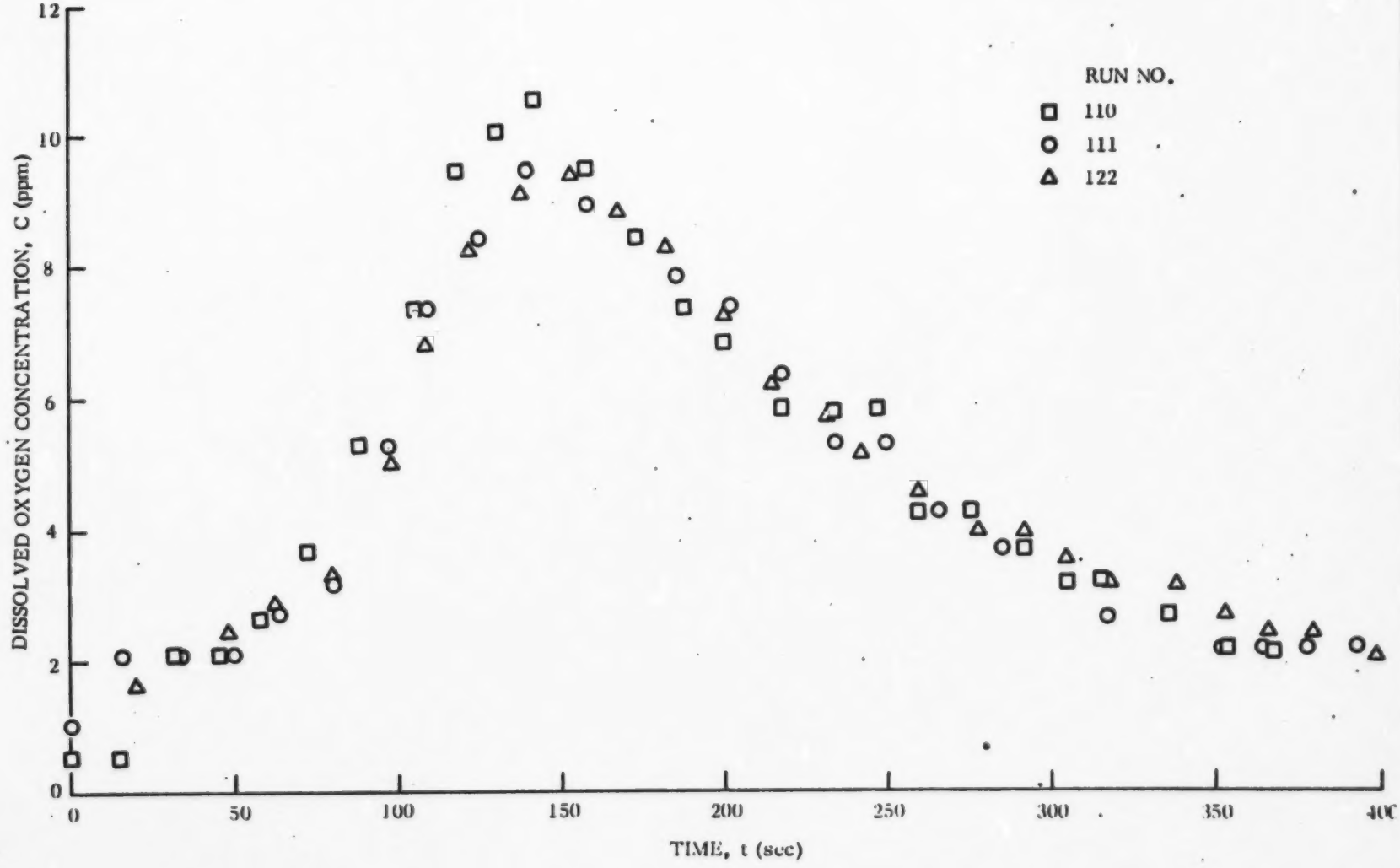

Figure 9 - Dissolved Oxygen Content at Column Outlet
Water flowrate: 31 gal/min
LOX flowrate: 12 g/min for 0.5 min.

of transfer for the whole column. The differential equation that applies to the first process is:

$$\frac{dC}{dt} = K_L a(C_s - C) \qquad (1)$$

where C = concentration of dissolved oxygen at time, t, in ppm,

t = time for transfer in hr,

C_s = saturation concentration of dissolved oxygen in water in equilibrium with a pure oxygen atmosphere in ppm,

K_L = mass-transfer coefficient per unit volume,

a = area through which transfer is effected. Since bubble size cannot be determined, the product

$K_L a$ = effective mass-transfer coefficient per unit volume, is determined. It has the unit, hr^{-1}.

If $K a$ is assumed constant, Eq. (1) can be integrated to yield:

$$\ln(C_s - C) = -K_L a \cdot t + \text{constant} \quad . \qquad (2)$$

The actual value of the mass-transfer coefficient is obtained by measuring the slope of $\ln(C_s - C)$ plotted <u>versus</u> time as shown in Figure 10.

In the case of bulk mass-transfer, the equation that applies is

$$\frac{dN}{dV} = K_L' a(C_s - C) \qquad (3)$$

where N = mass transferred per unit time in lb O_2/hr

V = volume of solution into which the oxygen is transferred and "K_L'" and "a" have the same significance as above.

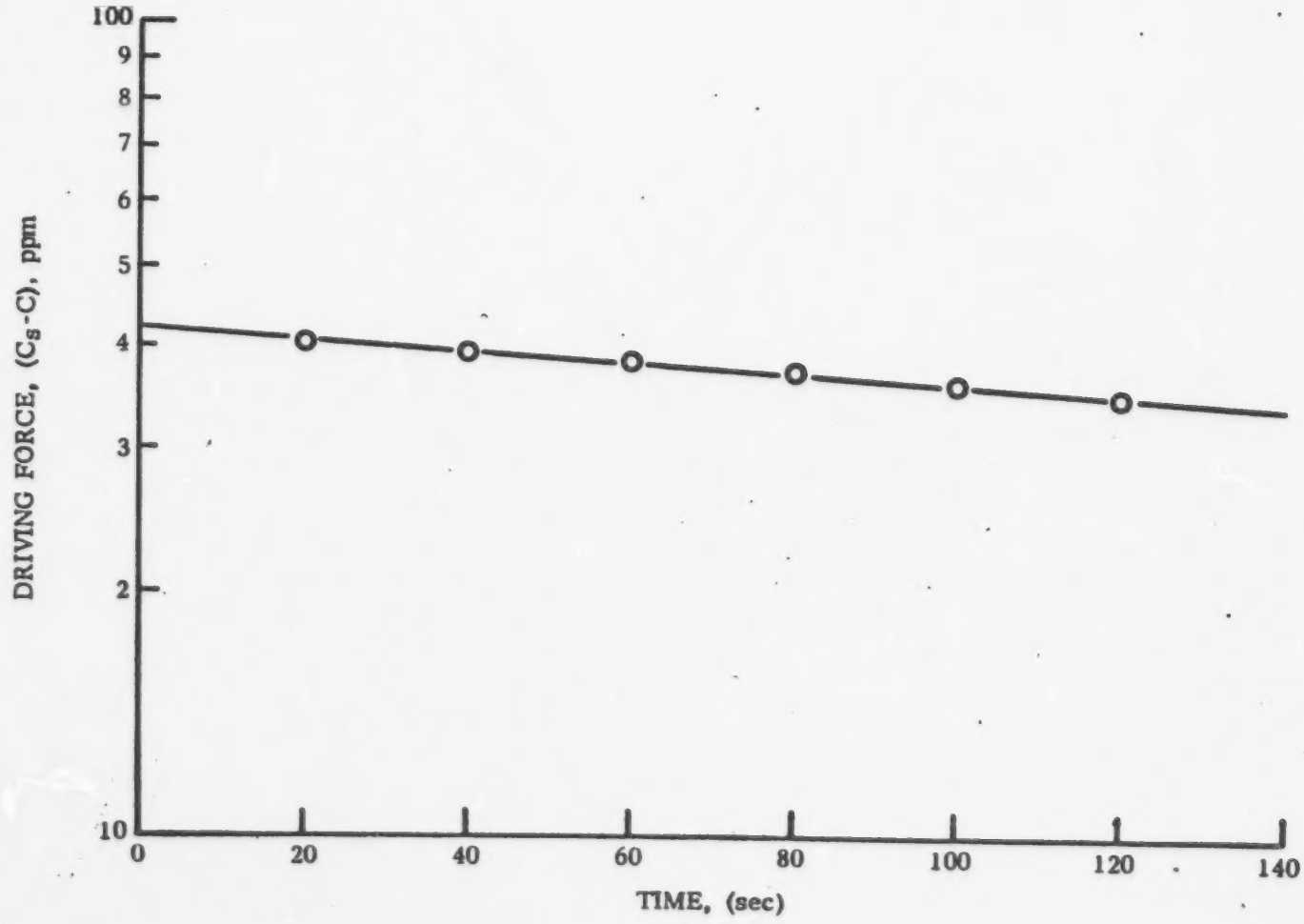

Figure 10 - Rate of Concentration Change During Oxygen Absorption (The Slope Of This Line is the Mass-Transfer Coefficient)

The rate of transfer is related to the concentration change in a mass of water by the equation:

$$\frac{dN}{dC} = \frac{L}{\rho} \tag{4}$$

where L = solution flowrate in lb/hr

and ρ = solution density in lb/ft^3.

Equations (3) and (4) can now be combined to yield

$$K_L'a(C_s-C)dV = \frac{L}{\rho}\,dC \quad . \tag{5}$$

By integrating from the initial to final state, Eq. (5) yields:

$$\ln \frac{(C_s-Ci)}{(C_s-Cf)} = \frac{K_L'a \cdot \rho V'}{L} \tag{6}$$

where Ci = initial DO in ppm and Cf = final DO in ppm

and V = volume of the transfer vessel in ft^3.

By rearranging, the expression for the bulk mass-transfer coefficient is obtained in terms of measureable parameters:

$$K_L'a = \ln \frac{(C_s-Ci)}{(C_s-Cf)} \cdot \frac{L}{\rho V'} \quad . \tag{7}$$

For most cases of calculating the mass-transfer coefficient, we used Eq. (2). We have, however, checked these calculations by applying Eq. (7) to randomly chosen experiments.

The equivalency of the two mass-transfer coefficients, $K_L a$ and $K_L' a$ is shown as follows:

$$N = AvC \tag{8}$$

where A = the column cross-sectional area in ft^2

v = the average solution velocity through the column in lb/hr .

This says that the amount of oxygen transferred per unit time is equal to the amount of water passing through a cross-sectional area of the contacting vessel in this time period multiplied by concentration of oxygen dissolved.

Now

$$\frac{dN}{dC} = Av, \text{ but } v = \frac{l}{t} \text{ or (where l is column height).} \tag{9}$$

Since v is independent of N or C, $v = \frac{dl}{dt}$ and $Adl = dV$, then

$$\frac{dN}{dC} = \frac{dV}{dt} \tag{10}$$

By rearranging, we obtain $\frac{dN}{dV} = \frac{dC}{dt}$. Therefore from Eqs. (1) and (3)

$$K_L'a(C_s - C) = K_L a(C_s - C) . \tag{11}$$

Thus $$K_L'a = K_L a .$$

Data Groups - Their General Impact and Validity

The data can best be grouped according to the type of experimental system used. The experimental systems were categorized in the section called "Experimental Program," and we will use the same groupings here. Results of replicate runs were averaged when the data from the runs were in close agreement.

Group (a). The data are presented in Table I. One obvious result was the low absorption efficiencies observed which led to a modification of the apparatus so that longer contact times could be obtained. Mass-transfer coefficients were not evaluated.

Group (b). The data are listed in Table II. They show that relative absorption efficiencies can be increased by baffling the exchange region and operating at relatively small, LOX/water, flow ratios. This was to be expected. These data do give the reader a feel for the reproducibility of the experiments. The calculated LOX mass-transfer coefficients are comparable to those for gaseous oxygen transfer studies.

Group (c). The data in Table III indicate that some of the runs operated at higher (up to 100%) "relative" efficiencies. The main reason for this dramatic increase in efficiency is additional contact time due to the extension of the column by a small-diameter, 7-ft glass tube on top of the original column. Nearly all of the mass transport takes place in the upper 7 ft of the column where all of the undissolved oxygen is in the gas phase. Thus, while it is no doubt interesting that this enhanced absorption efficiency, there is little in data of this sort to prove that LOX possesses significant practical advantages over gaseous oxygen. At high efficiencies, the question of the accuracy of the material balance becomes an important factor. Earlier in the report it was noted that the term "relative" efficiency was being used due to irregularities in operating procedure for the LOX-injection device. An attempt was made late in the project to "calibrate" this injection technique with the following result (95% confidence level):

$$LOX_{Actual}\ (g) = 8.2 + 0.77\ LOX_{Calibrated}\ (g) \pm 3.0$$

The variance associated with this equation is so large that it was not deemed worthwhile to update the LOX-flow and the corresponding LOX absorption-efficiency values in any of the data groups. Thus, we can place relatively little reliability on the efficiency data, other than for comparative purposes. However, the calculation for mass-transfer rate is based only on liquid-phase data, and these numbers are felt to be useful. These data provide the basis for the correlation of the mass-transfer coefficient with the Reynolds number developed later.

Group (d). The data in Table IV suffer from the same uncertainties as the previous data. They do show, however, that any temperature effects which may exist have no noticeable effects on the transfer coefficient over the range of temperatures studied. (Part of Group (c) data are reproduced for comparison purposes.)

TABLE I

RESULTS OF LOX INJECTION INTO A SEVEN-FOOT COLUMN OF WATER, T = 20°C

Run	Flowrate LOX (g/min)	Flowrate Water (gal/min)	Injection Time (sec)	Relative Absorption Efficiency (%)
21	8	27	105	5.7
22	8	27	85	5.3
27	17	27	30	3.0
28	17	27	150	4.8
29	20	27	150	4.0

TABLE II

RESULTS OF LOX INJECTION INTO A SEVEN-FOOT COLUMN OF WATER EQUIPPED WITH BAFFLES, T = 20°C

Run	Flowrate LOX (g/min)	Flowrate Water (gal/min)	Injection Time (sec)	Relative Absorption Efficiency (%)	Mass-Transfer Coefficient,* $K(hr^{-1})$
45	3	27	30	18.4	
46	3	27	30	16.5	
47	3	27	30	14.0	
48	1.3	27	30	10.5	
49	1.3	27	30	11.0	
50	1.3	27	30	12.0	
65	3	31	30	19.1	
66	3	31	30	15.0	
67	3	31	30	14.3	
68	3	31	30	16.8	
69	3	31	60	12.9	
70	3	31	60	16.2	
71	3	31	60	13.2	
72	3	31	120	11.3	
73	3	31	120	8.7	
74	3	31	120	10.3	
76-77 (avg.)	12	31	30	2.9	-1.3
78-81	12	31	60	5.6	3.0
82-84	12	31	120	4.4	3.6
85-86	12	31	30	5.5	3.1
87-89	12	0	30	2.4	4.3
90-92	12	0	60	3.3	4.9
93-95	12	0	120	2.7	5.9
96-98	3	0	120	7.6	4.5

* The units of the mass-transfer coefficient (hr^{-1}) are the results of solving Eq. (1), p. 19, for K.

TABLE III

RESULTS OF LOX INJECTION INTO A 14-FOOT COLUMN OF WATER WITH THE LOWER PORTION OF THE COLUMN EQUIPPED WITH BAFFLES, T = 20°C

Run	Flowrate LOX (g/min)	Flowrate Water (gal/min)	Injection Time (sec)	Relative Absorption Efficiency (%)	Mass-Transfer Coefficient, K(hr^{-1})
100-102	3	15	30	56.2	3.66
103-104	3	15	60	49.2	4.49
106-109	3	15	120	44.7	5.02
110-111-122	12	31	30	56.0	6.38
112-114	12	15	30	18.7	3.71
115-117	12	15	60	15.6	5.09
118-120	12	15	120	14.4	6.98
123-125	12	0	30	4.3	5.22
126-127	12	0	60	5.3	5.56
129-131	12	0	120	2.1	4.55
132-134	3	0	120	14.5	3.00
135	3	0	805 (steady state)	8.1	2.95
136-138	12	20	30	20.2	2.95
139-141	12	20	60	18.9	6.00
142-145	12	20	120	18.6	8.87
146-148	3	20	30	100.0	3.18
151-153	3	20	60	60.0	3.06
154, 155, 159	3	20	120	42.7	4.96
156-157	12	10	30	8.9	1.13
160	12	10	30	10.3	0.63
161, 163, 164	12	10	60	11.4	1.39
162, 165	12	10	120	10.8	3.50
166, 167	3	10	30	30.4	0.70
168, 170	3	10	60	36.7	1.53
171,172	3	10	120	30.0	3.06
173-174	12	5	30	7.5	0.66
174-175	12	5	60	5.2	1.20
177-178	3	30	30	100.0	6.43
228	3	0	120	6.2	2.2
230-231	9	0	120	3.4	3.4
229, 232	6	0	120	4.7	2.1
233-234	3	0	120	8.6	3.1
235	6	0	120	12.0	3.2
236	9	0	120	3.4	4.4

TABLE IV

EFFECT OF TEMPERATURE ON THE ABSORPTION OF LOX. DUAL COLUMN WITH 14-FOOT HEAD, LOWER COLUMN BAFFLED.

Run	Temperature	Flowrate		Injection Time (sec)	Relative Absorption Efficiency (%)	Mass-Transfer Coefficient, K(hr^{-1})
		LOX (g/min)	Water (gal/min)			
237-238	30	3	20	30	4.1	100.0
239-240	30	3	20	60	6.5	79.5
241-242	30	3	20	120	8.2	59.0
243-244	30	3	10	30	0.58	38.6
245-246	30	3	10	120	3.0	39.8
247-248	10	3	20	30	3.9	78.0
249-250	10	3	20	120	5.2	61.0
251-252	10	3	20	60	3.7	57.0
253-254	10	3	10	30	0.70	37.0
255-256	7	3	20	30	4.0	100.0
257	7	3	20	60	4.5	78.0
258	7	3	20	120	5.3	57.0
259-260	10	3	10	120	2.6	33.3
261-262	10	3	10	120	5.1	31.5
263	10	3	10	30	0.83	48.0
264	10	3	10	60	1.3	31.7
146-148	20	3	20	30	3.18	100.0
151-153	20	3	20	60	3.06	60.0
154, 155, 159	20	3	20	120	4.96	42.7
166, 167	20	3	10	30	0.20	30.4
168, 170	20	3	10	60	1.53	36.7
171, 172	20	3	10	120	3.06	30.0

TABLE V

EFFECT OF INITIAL DO ON BOTH RELATIVE ABSORPTION AND MASS-TRANSFER COEFFICIENT, T = 20°C

Run	LOX (g/min)	Water (gal/min)	Injection Time (sec)	Initial DO (ppm)	Relative Absorption Efficiency (%)	Mass-Transfer Coefficient, K(hr^{-1})
265-266	3	20	60	5.0	88.0	5.4
267-268	3	20	60	5.0	76.0	5.7
269-271	3	20	60	4.67	65.0	4.4
272-274	3	20	60	3.75	64.0	4.8
275-276	3	20	4/30	3.0	91.0	4.8
277-278	3	20	60	3.0	73.0	5.6
146-148	3	20	30	< 0.5	100.0	3.18
151-153	3	20	60	< 0.5	60.0	3.06
154, 155, 159	3	20	120	< 0.5	42.7	4.96

TABLE VI

EFFECT OF LOCALIZED STIRRING ON BOTH OXYGEN-ABSORPTION EFFICIENCY AND MASS-TRANSFER COEFFICIENT, T = 20°C, INITIAL DO > 0.5 PPM

Run	LOX Rate (g/min)	Water Rate (gpm)	Injection Time (sec)	Size (in)	Impellor (rpm)	Relative Absorption Efficiency (%)	Mass-Transfer Coefficient $K(hr^{-1})$
Top Column Off		(Head = 7 ft)			Baffles removed		
279-280	3	0	30	4	680	51.5	7.7
281-282	3	0	60	4	680	39.7	6.3
283-285	3	0	120	4	680	32.4	8.7
303-304	3	0	30	6	1,720	70.0	2.5
306-308	3	0	60	6	1,720	29.0	1.4
309-311	3	0	120	6	1,720	23.0	2.2
Top Column On		(Head = 14 ft)					
286-287	3	0	30	4	680	38.8	3.4
288-289	3	0	60	4	680	26.4	3.5
290-291	3	0	120	4	680	26.5	5.9
292	3	10	30	4	680	56.0	1.7
295 & 299	3	10	60	4	680	54.0	5.2
296 & 298	3	10	120	4	680	47.0	8.0
300-302	3	10	30	4	680	34.0	1.1
342-344	3	0	30	6	1,720	76.0	2.8
347-348	3	0	60	6	1,720	85.0	6.5
349-351	3	0	120	6	1,720	88.0	12.6
360-362	3	5	30	6	1,720	106.0	29.0
363-364	3	5	120	6	1,720	133.0	65.0

TABLE VII

FACTORS AFFECTING LOX AND GASEOUS OXYGEN ABSORPTION

Amount of Oxygen Injected (g)	Flow of Oxygen (g/min)	Period of Injection (sec)	Water Head (ft)	Water Flow (gal/min)	Relative Efficiency, Percent Absorbed		Mass-Transfer Coefficient, K(hr^{-1})	
					LOX	Gas	LOX	Gas
1.5	3	30	7	0	70	46	2.5	1.3
1.5	3	30	14	0	76	50	2.8	2.0
1.5	3	30	14	5	106	48	29.0	18.0
3.0	3	60	7	0	29	33	1.4	2.0
3.0	3	60	14	0	85	48	6.5	3.1
6.0	3	120	7	0	23	32	2.2	4.2
6.0	3	120	14	0	88	45	12.6	4.8
6.0	3	120	14	5	133	44	65.0	22.0
6.0	12	30	7	0	16	23	1.2	3.8
12.0	12	30	14	0	31	33	5.5	7.0
12.0	12	60	7	0	16	16	5.0	5.8
24.0	12	60	14	0	35	32	11.7	10.5
24.0	12	120	7	0	-	10	-	6.3
		120	14	0	27	24	21.3	16.5

TABLE VIII

EFFICIENCY OF ABSORPTION OF OXYGEN
IN A CONTINUOUS FLOW SYSTEM
Oxygen Flow = 25 g/min

Water Flow (gpm)	LOX Absorption		Gaseous Oxygen Absorption	
	O_2* (%)	DO** (%)	O_2* (%)	DO** (%)
31.0	15.0	14.0	13.0	14.0
5.0	5.0	1.6	10.0	1.1
2.0	1.0	0.6	0	0.6

* O_2 means calculation from gaseous oxygen not absorbed by the water column, measured instead by wet-test meter.

** DO means calculation based on dissolved oxygen in effluent water stream of absorption tower.

EVALUATION

Information From the Data

There is little to be gained from any attempt to correlate the data on absorption efficiencies with any of the system parameters because of the problems mentioned earlier. However, some qualitative judgments can be made. The data on mass-transfer coefficients have greater utility. A quantitative correlation between the mass-transfer coefficient and the properties of the system can be obtained by resorting to dimensional analysis. Dimensional analysis indicates that the dimensionless mass-transfer coefficient (the Sherwood number) should be a function of the Reynolds number (Re) and the Schmidt number (Sc). Since the Schmidt number contains parameters which involve properties of the fluids only, it will not enter into the correlation because we have been dealing with the same fluids throughout these experiments. It is therefore reasonable that the mass-transfer coefficient should correlate with the Reynolds number alone. As mentioned earlier, the degree of turbulence in the system was increased by lengthening the injection time; because of this fact, an attempt was made to obtain separate correlations for the three most commonly used injection periods of 30, 60 and 120 sec. The correlations which were obtained are shown in Figures 11, 12, and 13.

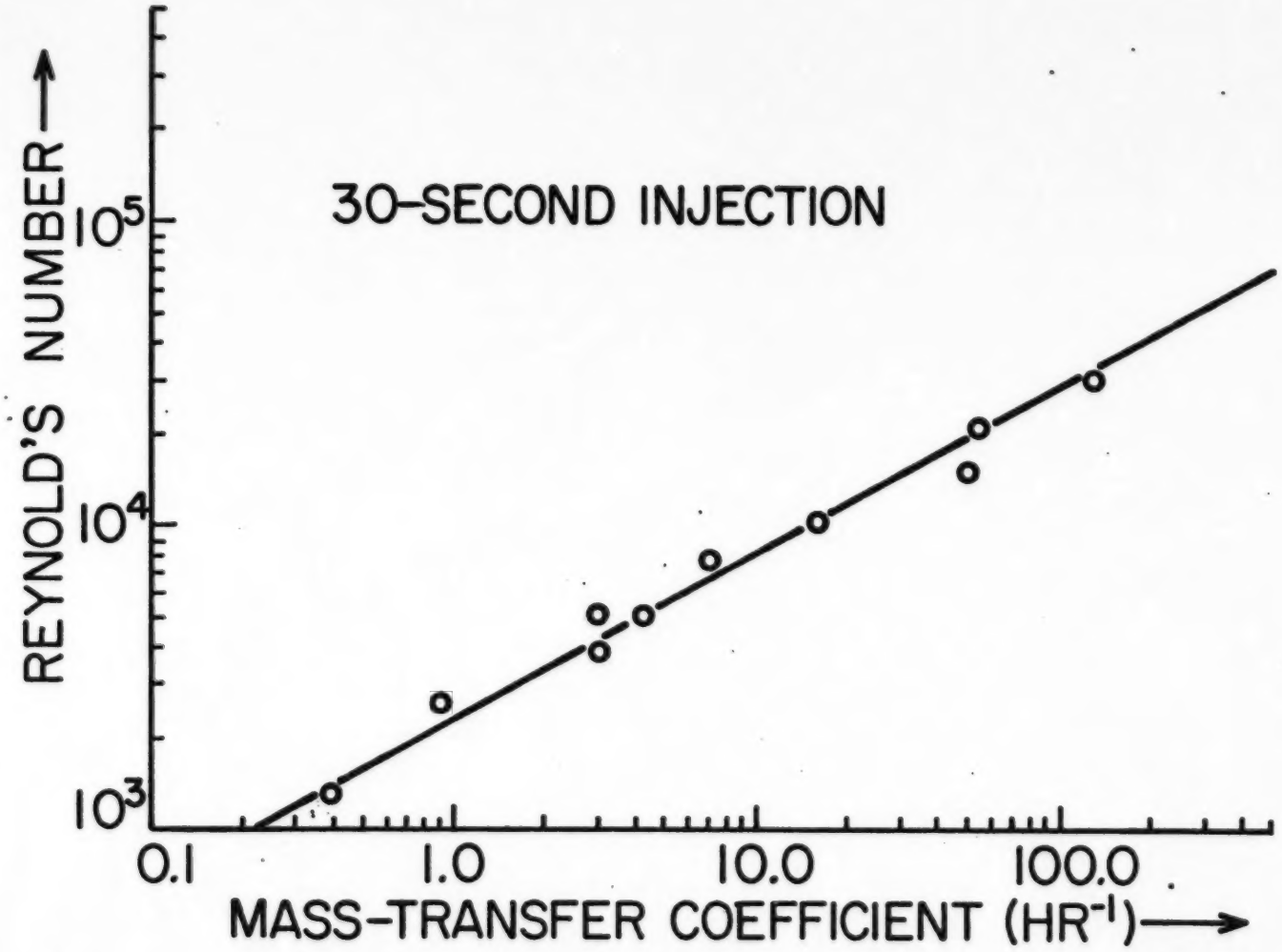

Figure 11 - Correlation of Mass-Transfer Coefficient with Reynolds Number, 30-Second Injection Period

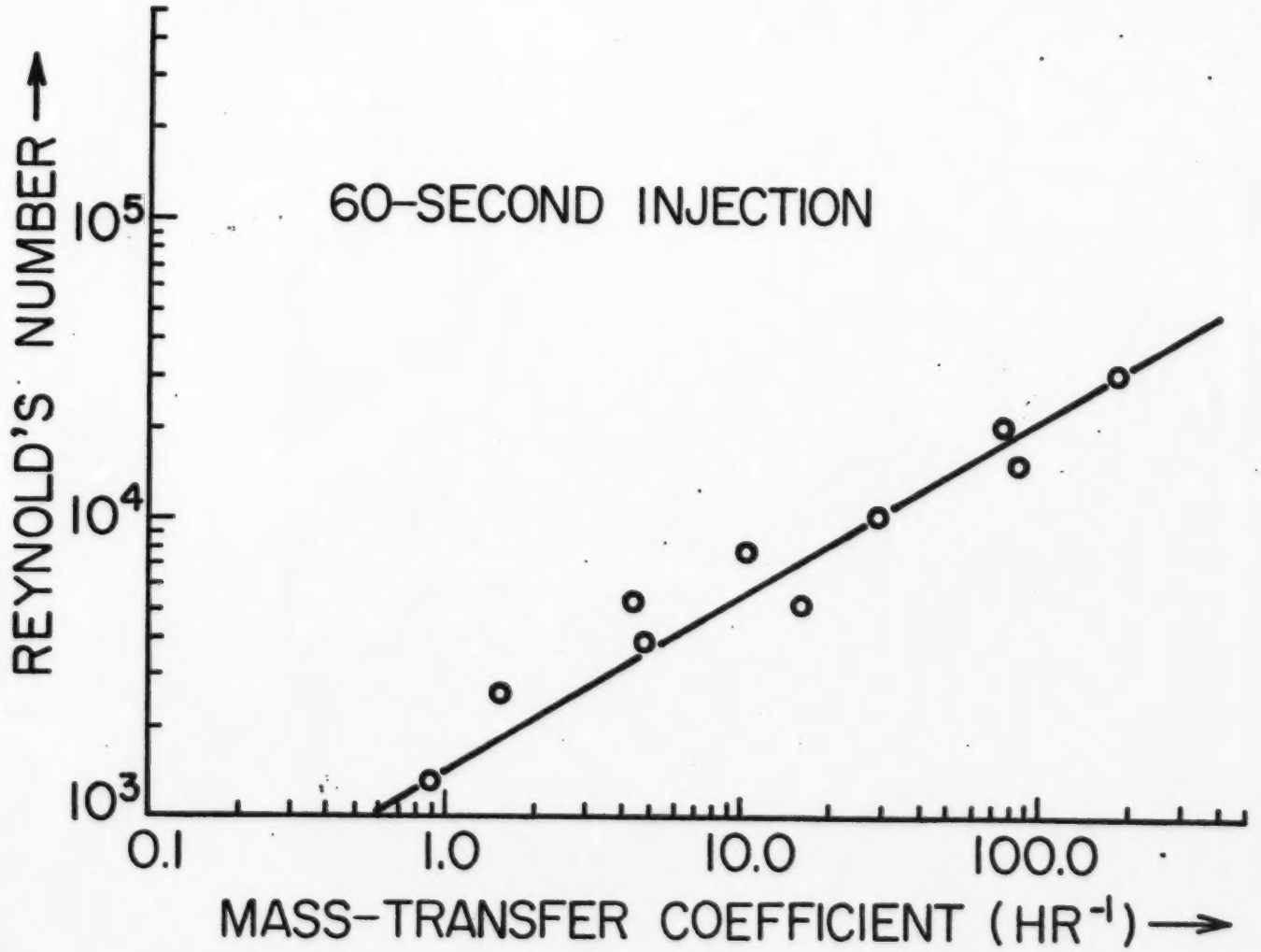

Figure 12 - Correlation of Mass-Transfer Coefficient with Reynolds Number, 60-Second Injection Period

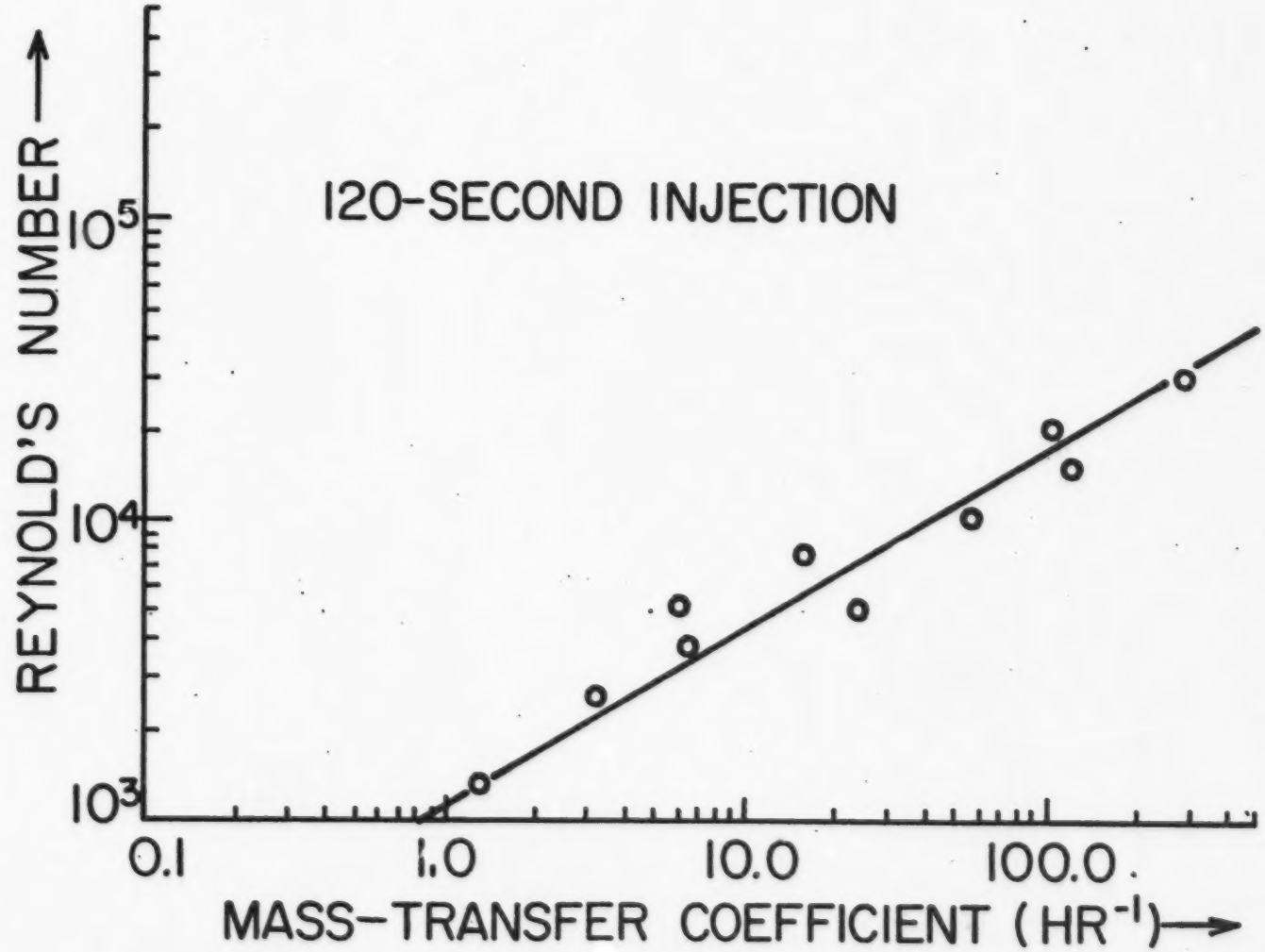

Figure 13 - Correlation of Mass-Transfer Coefficient with Reynolds Number, 120-Second Injection Period

Since in some cases the column had two different Reynolds numbers for each experimental run (due to the different diameters of the two column sections), there is some question as to which Reynolds number corresponds to the mass-transfer coefficient that was calculated. At any given mass flowrate, the Reynolds number in the top section of the column is four times the Reynolds number in the lower section of our column. By using the second calculational method discussed in the previous section, it can be shown that the Reynolds number which should be used in correlating the mass-transfer coefficients corresponds to the number in the lower column. It can also be shown that the ratios of the mass-transfer coefficients for the upper versus the lower portions of the column are equal to the ratio of the volumes of the upper and lower sections. The proof is as follows:

For a fixed initial and final DO, mass flowrate, and density, the ratio of Eq. (3) for the top column section to Eq. (3) for the bottom column section is

$$\frac{(K_L aV)_{Top}}{(K_L aV)_{Bottom}} = 1 \quad ;$$

therefore

$$K_L a_{Top} = K_L a_{Bottom} \frac{V_{Bottom}}{V_{Top}} \quad .$$

In other words, if all oxygen transfer occurred in the top section, but the concentration change used to calculate the mass-transfer coefficient were measured in the bottom section, the actual mass-transfer coefficient would be the one calculated, multiplied by the ratio V_{Bottom}/V_{Top}.

When the mass-transfer coefficients are increased by the ratio of the volumes as described in the preceding paragraph, they fall on the correlating line drawn from the original data. With the correlation shown in Figures 11, 12 and 13, it will be possible to extend the range of usefulness of these data by extrapolation. In other words, it will be possible to predict what the mass-transfer coefficient for a system similar to the one used would be if the Reynolds number were, for example, 100,000.

It is not surprising that these data correlate strongly with the Reynolds number. The same sort of correlation would be expected for gaseous oxygen. In fact, previously published mass-transfer data would lead one to expect a mass-transfer correlation of the form:

$$K_L a = f(Re, Sc) \quad \text{(see Iberall and Corder}^{5/}\text{)}$$

No gaseous data have been taken in a flowing water system similar to the one we have used, so it is not possible to obtain a comparison between mass transfer coefficients.

We can, however, compare with a correlation for wetted wall columns to determine if the mass-transfer coefficient in the gaseous system would be of the same order of magnitude as that for our LOX system. The correlation is

$$K_L a = \left[(0.023)\left(\frac{4}{D}\right)(D_v)\right] Re^{(0.81)} Sc^{0.44}$$

where

Re = Reynolds number

Sc = Schmidt number

D = Diameter of wetted wall column

D_v = Diffusion coefficient of O_2 in water

For a Reynolds number of 10,000 in a reasonably sized column, $K_L a \approx 3\ hr^{-1}$ which is the same order of magnitude as we have found.

Economic Considerations

The cost of pure oxygen to the consumer is predicated on the rate of consumption and distance to source of production. An economic breakpoint exists at the consumption rate of about 25 tons/day since at this point, when no other untoward economic factors occur, a separation plant would be erected at or near the site of consumption.

If the demand were over 25 tons/day, the oxygen would be supplied as gaseous oxygen by pipeline. On the other hand, smaller quantity consumption of oxygen could not economically support a plant and thus the oxygen would be transported to the site of consumption as LOX.

Four major, industrial gas suppliers were queried as to the pricing schedule by requesting the cost for supplying oxygen to 10 different locations. Four scales of oxygen requirements, subsequently established, were somewhat related to the communal BOD load. These are listed below:

Location	Oxygen Requirements (lb/day)
Chicago, Illinois	200,000
Kansas City, Missouri	200,000
Buffalo, New York	200,000
Athens, Georgia	25,000
Corvallis, Oregon	25,000
Springfield, Massachusetts	25,000
Carlyle, Illinois	5,000
Henderson, Kentucky	5,000
Las Cruces, New Mexico	1,000
Show Low, Arizona	1,000

The results of the responses are presented in Figure 14. The pricing schedules of the four companies are quite close to each other. Two of the companies quote LOX prices that include rental of storage facilities, while the other two companies quote lower LOX prices with additional costs for rental of storage tanks. All four suppliers would have the customer provide a concrete foundation and fencing at his own expense. The sites with lower level LOX consumption would have storage capacity with several days' consumption at hand. Reorders are usually placed when the storage facility has been drained to about 30% of capacity.

LOX is transported by truck and tank car. Quoted prices include delivery within a 100-mile radius of the separation plant. In some of the more remote locations of the West, the price of LOX could double due to delivery costs. Delivery costs include both transportation and evaporation. LOX can be piped, but costs of $10 to $30/linear ft for cryogenic piping limit the distance of this transport method.

When oxygen is produced by on-site liquefaction and distillation of air, the delivered product is gaseous oxygen since the heat of vaporization of the liquid can be used to cool the air that is to be liquefied. Tonnage oxygen costs drop to $10/ton only at the level of 1,000 tons/day consumption. Only metropolitan New York City would produce domestic wastes with a BOD requiring this amount of oxygen.

The minimum price of pure oxygen is related to the cost of power by the relationship that 350 kwh is required for the production of 1 ton of pure oxygen. The Kansas City industrial rate of slightly less than $0.02/kwh sets a floor of about $7/ton oxygen. Only in plants producing a very high tonnage of oxygen daily does this power requirement become the major factor in the cost of pure oxygen in relation to capital costs and other operating costs.

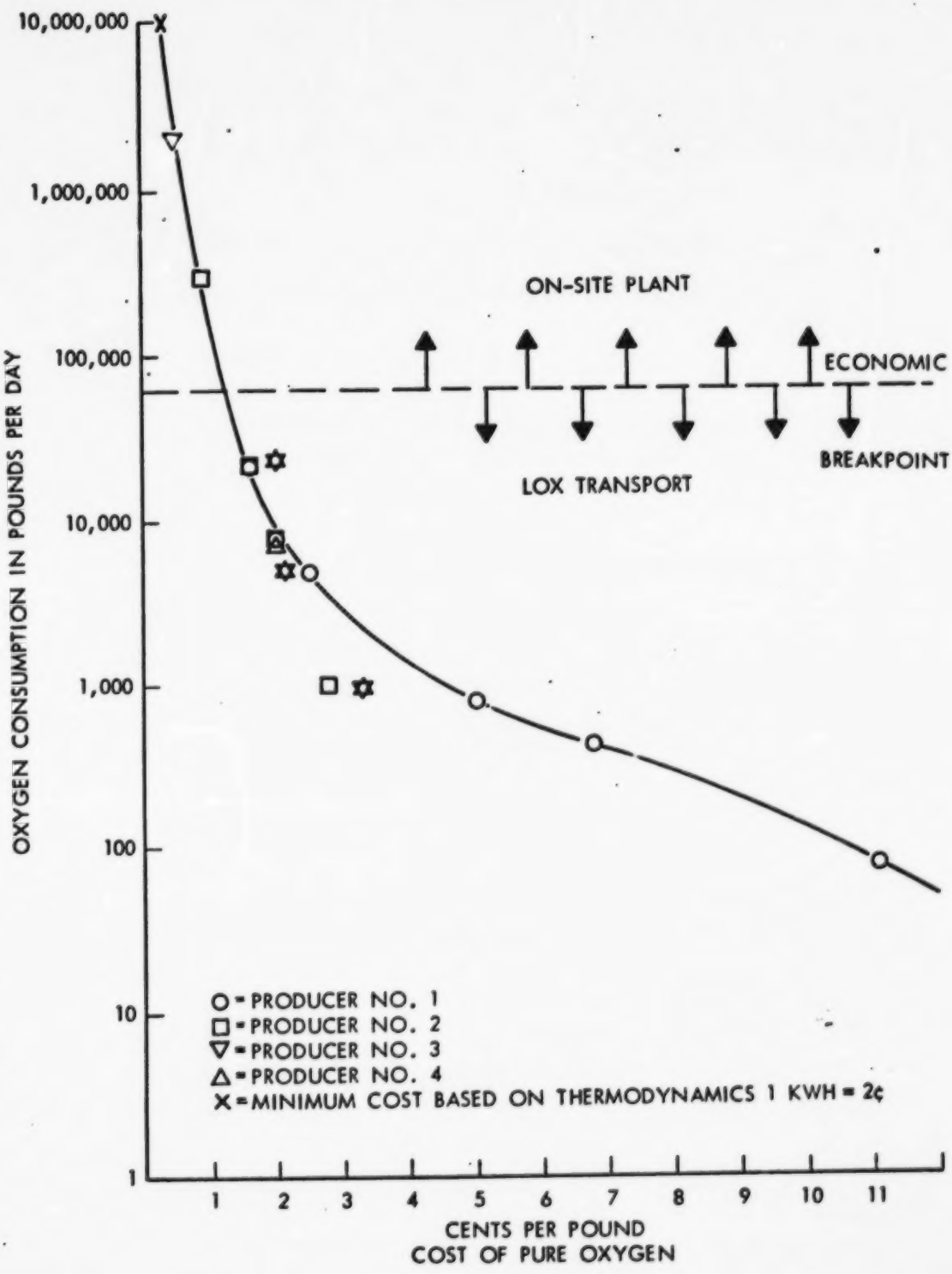

Figure 14 - Cost of Pure Oxygen

Speece[6] has conducted a modeling study of the solution of diffused oxygen in water. Under certain conditions, 100% absorption was predicted. Some power must be expended to accomplish this, but if the operating power costs are assumed small in relation to the cost of the oxygen, oxygenation may be compared with alternative processes as seen below:

Process	Oxygen Transfer Rate (lb/kwh)	Cost/lb O_2 (2¢/kwh)
Air sparger	3.3	0.61¢
Surface aeration	4.7	0.43¢
Brush aerator	5.4	0.37¢

It can be seen from these cost figures for oxygen transferred by aeration that a plant operating with pure oxygen as a source of DO must either have distinct design or operating advantages or else consume in the order of several thousand tons of oxygen per day if the pure oxygen process is to be competitive with aeration.

If processes utilizing pure oxygen are developed, the interesting economic question arises regarding the relative attractiveness of LOX versus gaseous oxygen as a source of oxygen for water treatment. Although LOX is generally more expensive to produce at any given site, it is less expensive to transport and store for use. Since the requirement for stream and treatment oxygen may be quite cyclic in an urban area, the economically optimum situation for oxygen supply might entail the construction of a large oxygen plant close to an important continuous user (a steel mill, for instance). The overcapacity from this plant could then supply the water treatment needs (as LOX) of the megalopolis. No analysis of the attractiveness of such an arrangement has been made here, although this study does indicate that (as far as mass transfer is concerned) LOX is at least as attractive as gaseous oxygen. The deciding factors will evidently be transportation economics.

Overall Evaluation

Although the experimental system devised did not produce good data on absolute sorption efficiencies throughout most of the program, several useful things have been learned.

1. Good mass-transfer coefficient data have been obtained and correlated, and these correlations may be useful in terms of scale-up to larger systems,

2. The mass-transfer coefficient data indicate that LOX may be a somewhat more readily absorbed source of oxygen than gaseous oxygen,

3. The economics of transportation may be a controlling factor,

4. An experimental system to study the use of LOX effectively should have a water-flow capacity much greater than 100 gpm, and

5. Several design parameters, which were thought to have possible impact on absorption rates, were shown to be unimportant in their effect.

There is merit to considering a considerably larger experimental system. If there are advantages to the use of LOX in relation to gaseous oxygen, they will exist only when there is LOX actually present in the system. Only a very large experimental system could contain the volume of water or have the necessary throughput to accommodate large slugs of injected LOX. The LOX slug should be of such an amount that a significant portion would remain in the liquid state for an appreciable time.

Conclusions

1. This study has not shown any difference in the efficiency of solution of oxygen as liquid *versus* oxygen as gas in the experimental system used. This system was limited to a maximum absorption efficiency of 15%.

2. Conclusion 1 does *not* preclude the possibility that LOX may have an advantage over gaseous oxygen in a large system. The data indicate that LOX mass-transfer coefficients are *at least* as high as those for gaseous oxygen.

3. Gross turbulence appeared to be more effective in increasing absorption than localized turbulence; i.e., highly turbulent flow through the absorption column was more effective than turbulence created by stirring.

4. Higher mass-transfer coefficients are generally observed for longer injection periods.

5. It is possible to reach a DO concentration of up to 30 ppm by injecting LOX or by injecting gaseous oxygen.

6. Increasing the contact time, either by baffles or by increasing the downward flow of water (countercurrent to LOX flow), increased the efficiency of absorption but not the mass-transfer coefficient.

7. Increasing the LOX-injection rate increased the mass-transfer coefficient, but decreased the absorption efficiency.

8. Varying the water temperature from 7° to 30°C had no apparent effect on the absorption efficiency.

9. The initial DO content of the water did not appreciably affect the mass-transfer coefficient.

APPENDIX A

SCOPE OF WORK

FEDERAL WATER QUALITY ADMINISTRATION
CONTRACT 14-12-168 WITH THE MIDWEST RESEARCH INSTITUTE

OXYGENATION OF AQUEOUS BODIES WITH LIQUID OXYGEN, "LOXination"

The contractor will provide the necessary personnel, materials, and facilities, and will exert his best efforts to perform the research and engineering development studies that will determine the requisite parameters for the oxygenation of aqueous bodies with liquid oxygen (LOX). A detailed chronological description of the studies that will be conducted is presented below:

1. The design of the experimental apparatus that will be used to study the interaction of LOX with aqueous bodies will be completed and working drawings will be prepared. The preliminary design that has already been completed calls for construction of a tower comprising multiple sections of 12-in. diameter borosilicate glass (Pyrex Double Tuff), separated by narrow sections of 316 stainless steel. The glass sections will permit visual and photographic observation of the phenomena occurring within the column, while the stainless steel sections will permit the introduction of liquid streams as well as the instrumentation necessary for these studies. The column has been designed to allow pressurization to 30 psia. The liquid oxygen inlet lines will be insulated by use of vacuum-jacketed tubing. A bleed line will be placed just at the inlet to the column to ensure that the oxygen is introduced into the column in the liquid state.

The design factors remaining to be completed include the structure necessary to support the apparatus, the water pumping equipment, and specifications for the insulation of the lower end of the column.

2. The experimental apparatus with its appurtenances will be constructed in our shops. It will be installed in a laboratory containing safety features that will minimize hazards associated with the handling of LOX. Hazards to be recognized in handling LOX include: (1) explosive mixtures which form when LOX comes in contact with reducing substances, (2) burns and frostbite which may occur when low-temperature LOX or lines transmitting LOX come in contact with tissue, and (3) the extremely high pressures which can develop in a closed system if the system is allowed to warm up. To minimize these hazards we shall exercise scrupulous housekeeping, protect handlers of LOX with face shields and insulated gloves, and ensure that adquate bubble-off lines are built into each piece of apparatus. The laboratory will be well ventilated to ensure that unusually high levels of gaseous oxygen do not build up, and the additional precaution of an atmospheric oxygen monitoring meter with safety alarm will be installed.

3. When completed, the experimental apparatus will be tested for performance according to the design criteria of (1) hydraulic flow, (2) ability

to deliver oxygen in the liquid form, (3) minimization of heat input from external sources, and (4) performance of the associated instrumentation.

4. The first studies will be conducted by measuring the effects resulting from batch injection of LOX into a static water column. This is one of four possible variations that also include batch injection of LOX into a flowing water column, continuous injection of LOX into a static water column, and continuous injection of LOX into a flowing water column. These latter three conditions will be evaluated in subsequent experiments during these first studies.

The LOXination phenomena will be studied by making visual and photographic observations of the interface between the liquid water and the liquid oxygen. This information will help establish the actual mechanism of oxygen transfer. Additionally, mass transport phenomena will be studied by establishing oxygen concentration profiles by means of polarographic oxygen probes placed strategically throughout the apparatus. Heat transfer phenomena will be studied by measuring temperature profiles with Chromel-Alumel thermocouples.

The important process variables to be studied are:

(a) Temperature: The effect of temperature will be determined by employing water with initial temperatures of 4°, 10°, 20°, and 30°C. These temperatures are representative of the most probable range of temperatures to be encountered in polluted natural waters or wastewater streams.

(b) Initial Dissolved Oxygen Level: Inlet water with an initial dissolved oxygen level of 0, 10, 20, and 40% of saturation will be studied.

(c) System Pressure: The column will be pressurized either by employing excess gas pressure or by increasing the hydrostatic head. Pressures of 1, 1.5 and 2 atmospheres will be studied.

(d) Geometry of the Column: The effect of geometry will be evaluated by using length-to-diameter ratios of 2, 6, and 10. Baffles will be introduced to study their effect on changes in flow pattern and the resultant changes in the rate of oxygenation.

(e) Water Flow Rate and Column Height: The relationship between oxygenation and both residence time and flow regime will be determined by measuring the rate of oxygenation at various flow rates and column heights. The residence time, which is the ratio of the column height to the average velocity, will be selected so that the dimensionless parameter, V/Lk, will

have the values of 0.25, 1.0, and 4.0. In this parameter, V is the average velocity in ft/sec, L is the height of the contacting vessel in ft., and k is the rate constant for the specific rate of absorption in sec^{-1}.

Flow regimes will be selected so that the effect of laminar, transition, and turbulent flow will be measured. To achieve these types of flow, the flowrate will be varied to give Reynolds numbers of 0, 500, 2500 and 5000.

(f) The Mechanism of Creating the LOX-Liquid Water Interface: This mechanism will be elucidated by adding LOX at various points in the water column and observing the physical breakup of the LOX stream or slug. Various dispersal devices such as impellors, impingers and multiorifice distributors will be tested for their ability to produce optimum-size LOX globules. The criterion for optimum size will be the maximum absorption of oxygen in the shortest time period.

5. The results of all of the experiments which are described above will be tabulated, correlated, and interpreted to establish relationships among the numerous system variables and the phenomena involved in oxygenation of aqueous bodies by LOX. The experimental apparatus will then be modified, if necessary, to produce the most efficient addition of LOX to aqueous bodies.

6. The requisite parameters for the oxygenation by LOX of water from naturally occurring aqueous bodies will be determined. Among the waters that will be studied are, (a) Missouri River water, (b) effluent from the Blue River Sewage Treatment Facility at Kansas City, Missouri, (c) real or synthetic sewage treatment plant effluents that contain a higher than usual level of LAS, and (d) industrial effluents such as would be encountered in the pulp and paper industry.

7. The interaction of LOX with sludges from domestic wastewater and natural benthic sludges will also be measured. This interaction is important because in many applications of LOXination, the bottom of the LOXination vessel may be a natural river bottom or a sludge-holding tank, in which the bottom will be covered with dispersed organic material.

8. When all of the design parameters have been established by laboratory and field investigations, a precise economic comparison of LOXination with other artificial aeration techniques will be prepared. The results of this analysis along with the field testing will determine whether a large-scale demonstration project is feasible.

9. Throughout the course of the engineering study, due attention will be given to the eventual application of LOXination to field sanitary engineering practice by continuous recognition both of its technical feasibility and the economic requirements. Although this study has been designed to examine the application of LOXination to the abatement of water pollution, any phenomena which affect air quality or land values are important factors to be recognized and evaluated. Thus, the effect of large-scale LOXination on the total environment will be an important part of the study.

10. The senior investigators on the project will recognize the necessity to keep abreast of advancements in asscciated scientific and engineering fields by a regular program of literature surveillance, attendance at related scientific and technical meetings, and personal contact with other technical people in the field of sanitary engineering.

Close liaison will be maintained between the senior investigators and the Project Monitor as well as other interested personnel of the FWPCA. Informal monthly letter reports will be sent to the Project Monitor. A Final Report will be issued following completion of the project in numbers and in the style as requested by the FWQA.

APPENDIX B

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